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FIRST RESULTS OF RUNNING THE LHC WITH LEAD IONS AT A BEAM ENERGY OF 6.8 Z TeV*

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Abstract

A two-day test of operation with Pb ion beams was carried out in the CERN Large Hadron Collider (LHC) in 2022, with the aim of gaining experience in view of the future high luminosity heavy-ion physics runs from 2023 onwards. The LHC experiments received the first Pb-Pb collisions at a record energy of 5.36 TeV centre-of-mass energy per colliding nucleon pair (beam energy 6.8 Z TeV). Bunch trains created with a new production scheme in the injectors, including slip-stacking, were injected into the LHC, with the collimation of nuclear beams with bent crystals tested along with a new collimation scheme for collision products. This paper describes the conditions and outcomes of these tests, which are critical steps in the upgrade to higher luminosity.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN is built to accelerate and collide protons or nuclei in two counter-rotating beams (called B1 and B2). Two long LHC runs have been carried out: Run 1 (2010–2013), and Run 2 (2015–2018). At the time of writing, Run 3 (2022–2025) is ongoing at a record beam energy of 6.8 Z TeV. One month per operational year is typically dedicated to the heavy-ion physics programme with Pb-Pb or p-Pb collisions [2, 3]. This programme will continue in Run 3 and Run 4 (2029-2033)[4, 5]. A few short pilot runs at low intensity, e.g. using Xe beams [6], have also been performed, with an oxygen-oxygen and oxygen-proton run foreseen to take place in 2024.

For Run 3, a number of upgrades have been carried out in order to improve the LHC performance with heavy ions, including both the beam production scheme in the injectors [7], as well as the safe handling of beam losses in the LHC through installation of new collimators. The upgrades, carried out within the LIU [7] and HL-LHC projects [8, 9], should enable about 50% higher ion beam intensity in the LHC compared to Run 2, and more than a factor 6 higher luminosity at the ALICE experiment [10], which is specialised in heavy-ion collisions and has itself undergone major upgrades to accept the higher luminosity.

Following a re-scheduling of LHC operation in 2022, the initially planned 1-month Pb-Pb operation period at the end of 2022 was postponed to 2023. Nevertheless, a 2-day test with Pb beams was performed on 17-19 November 2022.

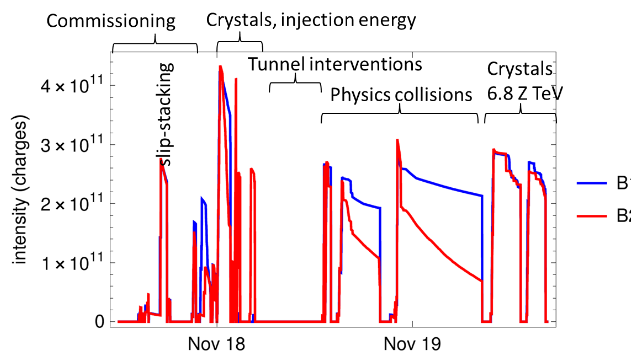

Figure 1: The intensity over time in the two LHC beams during the test.

The goals of the test were to provide first Pb-Pb collisions to the experiments at a record beam energy of 6.8 Z TeV (up from 6.5 Z TeV in 2016) and to test new hardware and operational procedures that future heavy-ion physics operation will rely on. This article describes the key activities and achievements from the 2022 test and discusses possible implications for future heavy-ion operation. The crystal collimation [11–14], which is deployed to increase the performance of the LHC standard collimation system [15–18], is described in another paper [19].

COMMISSIONING AND SLIP-STACKING

An overview of the beam intensity evolution during the different stages of the test is given in Fig. 1. Commissioning started with single Pb bunches from the injectors to set up the transfer lines to the LHC and the LHC RF capture. This process went smoothly and the first circulating Pb ions in the LHC were present in about two hours. However, some hardware problems has to be solved in attempting to accelerate the Pb beams to 6.8 Z TeV, necessitating a tunnel intervention and a rescheduling of the beam test programme at short notice.

Following single-bunch injections, 8-bunch trains with 50 ns spacing were successfully injected in the LHC for the first time. These beams were produced using a new scheme in the injectors, relying on momentum slip-stacking in the SPS [7]. In this process, two bunch trains with 100 ns bunch spacing were interleaved to form a shorter 50 ns train. Thanks to this technique, about 70% more bunches can be injected into the LHC compared to the previous scheme with 75 ns spacing although the projected maximum intensity per bunch is slightly lower.

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The injected intensity and emittance (2.3×10^8 Pb ions per bunch with 1.5 µm emittance) were well beyond the upgrade target in Ref. [7]. This is a very encouraging result. However, future operation relies on 56-bunch trains, which is still to be validated. Some degradation in intensity and emittance is expected for these longer trains due to the longer injection plateau required in the SPS.

COLLISIONS

Once the issues preventing acceleration had been fixed, the LHC was set up for collisions at the new record energy of 6.8 Z TeV. In order to expedite testing, the standard magnetic cycle and optics for proton operation were used. After reaching 6.8 Z TeV, the β^* (the β-function at the collision point) was reduced to 0.6 m at ATLAS and CMS, 2 m at LHCb, while remaining at 10 m in ALICE as for pp collisions. The β^* was kept constant in the test with the β^*-levelling used for protons not deployed.

The larger β^* was a disadvantage for ALICE, since it significantly reduced the achievable luminosity. In addition, the small β^* and resulting higher luminosity at the other experiments caused a rapid burn-off of the beam that even further reduced the ALICE luminosity. Reducing the β^* at ALICE to its target heavy-ion running value of 0.5 m would have required significant commissioning time that could not fit within the test schedule. Instead, ALICE was partly compensated by filling patterns constructed so as to give a larger number of colliding bunch pairs at ALICE, and by introducing separation levelling at ATLAS and CMS to limit their luminosity and hence increase the beam lifetime. This separation leveling was only performed after the first hour of collisions, so that ATLAS and CMS could still take data at the highest achievable event rate in the test.

Two fills were planned, with slightly different configurations. After a first unsuccessful attempt, which failed due to a beam dump on losses caused by a wire scanner emittance measurement, the beams were successfully brought into collision at all experiments. In this first physics fill, three single bunches were injected at a time from the SPS for a total of 20 bunches per ring (with 16 colliding pairs at ALICE and 8 at the other experiments). This respected the machine protection limit of 3×10^{11} total charges per ring, below which certain interlocks can be masked and validation requirements are less stringent. For the remaining machine protection checks required, four non-colliding bunches per ring were excited using the transverse damper to provoke controlled losses in so-called loss maps [15, 20, 21]. The observed beam loss pattern was validated after which "stable beams"[1] could be declared.

The first fill was kept for about 2.5 h, after which a second fill with higher luminosity was prepared, using two slip-stacked 8-bunch trains per ring together with a few single bunches. Because of the very good bunch intensity, a total of only 18 bunches could be injected in B1 and 19 in B2

[1] This is a machine mode with colliding beams where it is safe for the experiments to turn on their detectors

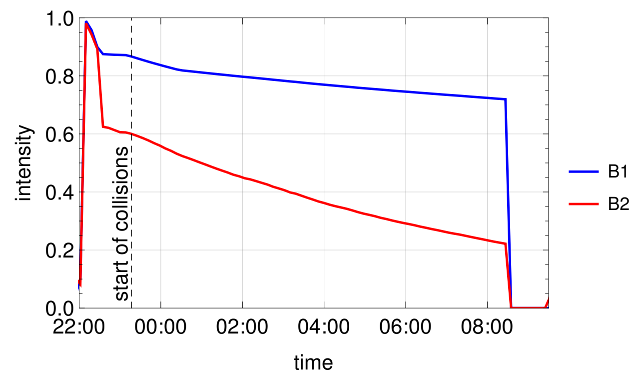

Figure 2: The relative intensity over time in the physics fill with slip-stacked beams for the two beams. The dashed vertical line indicates the start of collisions in this second physics fill.

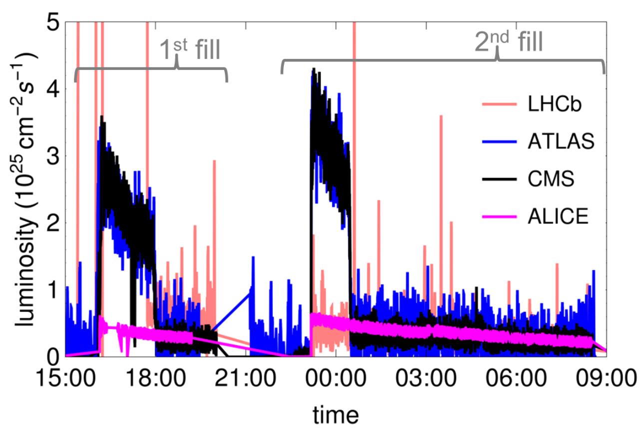

Figure 3: The recorded instantaneous luminosity at the four LHC experiments over the two physics fills.

before reaching the allowed limit of 3×10^{11} charges. This resulted in 18 colliding pairs at ALICE, 8 at ATLAS and CMS, and 3 at LHCb.

In the second fill, the beams were kept colliding for just over 9 h. The relative intensity evolution in this fill is shown in Fig. 2. A very large longitudinal beam loss of almost 40% occurred on B2 during the energy ramp, with the B2 losses also higher than for B1 during collision. This issue, seen also in other ramps, was finally solved in the very last ramp after corrections to the RF loop settings. This is not expected to be a limitation the 2023 ion run. For B1, a 10% intensity loss occurred between injection and collision, which is yet to be fully understood.

The instantaneous luminosity at all experiments over the two physics fills is shown in Fig. 3. It reached about 4.5×10^{25} cm^{-2}s^{-1} at ATLAS and CMS, and 6.1×10^{24} cm^{-2}s^{-1} at ALICE, which due to the limited number of bunches and larger β^* is about three orders of magnitude below the value expected in the 2023 high-intensity Pb-Pb run [5]. In total, an integrated luminosity of about 0.3 b^{-1} was collected at ATLAS and CMS, 0.13 b^{-1} at LHCb and 0.15 b^{-1} at ALICE. The latter number corresponds to about 10^6 events. It should

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be noted that these numbers carry a significant uncertainty, since the reported luminosity from the experiments had not been calibrated in detail.

DISPERSION SUPPRESSOR COLLIMATION

One very important upgrade for Run 3 was the installation of dispersion suppressor collimators (TCLDs) around the ALICE experiment. The TCLDs are needed to intercept losses of one-electron ions created by bound-free pair production (BFPP) in ultraperipheral collisions. These losses represent a continuous power of up to about 165 W that would otherwise quench the superconducting magnets they impact [22–25]. In Run 2, the ALICE luminosity was levelled at 10^{27} cm^{-2}s^{-1} to respect the maximum readout rate of the detector meaning that the beam losses remained safely below the quench limit. In future runs, an orbit bump will be used to displace the losses from the magnet at the first dispersive peak downstream of the collision point, to the TCLD location. This technique allows the upgraded ALICE detectors to exploit six times higher luminosity.

To test the principle of this new BFPP mitigation, the beam loss patterns were studied around ALICE, measured with beam loss monitors (BLMs) as shown in Fig. 4, where the collision point is in the centre. The upper figure shows the measured losses with the TCLDs fully open and without orbit bump. The BFPP losses are clearly visible as localised peaks on either side of the collision point ($s \approx 2950$ m and $s \approx 3720$ m). In the lower plot, an orbit bump of 4.7 mm has been applied on the left side, and the left TCLD has been inserted to a setting of 100 σ. As can be seen, the high loss peak in the cold magnetic region at $s \approx 2950$ m is then effectively suppressed and replaced by a lower loss on the TCLD itself (black bar at $s \approx 2900$ m). Even though the loss alleviation has not yet been tested with full luminosity, this result demonstrates that the losses can indeed be effectively directed away from the magnet and onto the collimator, a crucial step towards reaching the future performance goals [5].

ALICE CROSSING ANGLE

The crossing angle of the beams at the ALICE experiment is limited by the acceptance of the zero-degree calorimeter (ZDC). The ZDC intercepts spectator neutrons from the collisions, which would hit the upstream machine aperture if the angle at which they emerge is too large. In Run 2, the limit was a net full crossing angle of 120 µrad [2], the value that was used operationally. It is estimated that a larger net angle of 200 µrad will be needed for future operation due to the higher intensity [4]. To allow this without shadowing the ZDC an injection protection collimator had to be moved and modified during the recent long shutdown of the LHC to create a larger gap. To validate that ALICE have an equivalent ZDC coverage with the larger angle, the two physics fills were performed with different net crossing angles (200 µrad and 112 µrad). The full analysis by ALICE of the data taken in these configurations is ongoing, but first results confirm that the ZDC acceptance is sufficient with 200 µrad. This is another key result for the feasibility of the future baseline configuration for heavy ions in the LHC.

[2] The net angle is the superposition of the crossing induced by an external crossing bump and a local spectrometer compensation bump.

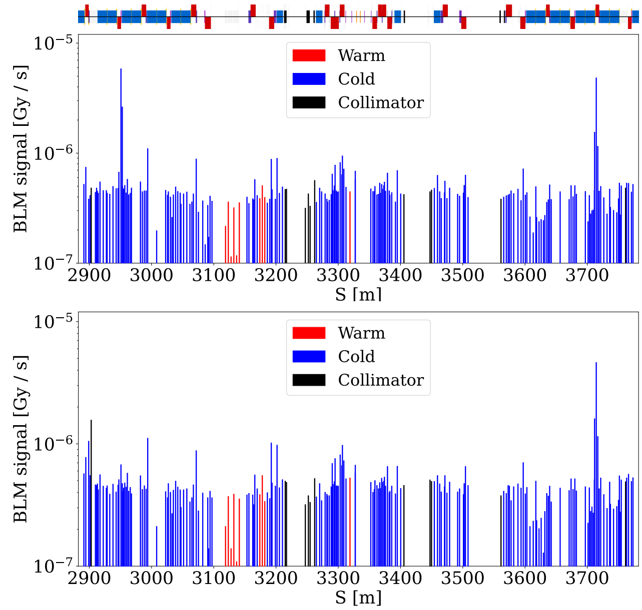

Figure 4: The recorded loss pattern around ALICE on cold and warm elements, and on collimators, without (top) and with (bottom) the orbit bump and closed TCLD collimator on the left side. The machine lattice is shown above.

CONCLUSIONS

A two-day test with low-intensity Pb ion beams in the LHC was performed in November 2022, to provide first collisions to the LHC experiments at a record heavy-ion energy of 6.8 Z TeV and to test key concepts of the configuration for future high-intensity physics. The test was very successful and all key goals were achieved. 8-bunch trains produced using a new slip-stacking scheme in the SPS were successfully injected and collided in the LHC, with the LHC experiments recording a small data sample in two dedicated physics fills. Crystal collimation was successfully tested [19], and the feasibility of alleviating critical collision losses using newly installed collimators was demonstrated. The acceptance of the ALICE ZDC with an increased net full crossing angle of 200 µrad was also verified. As a result, all upgrades for future high-luminosity heavy-ion operation have been, to a large extent, tested providing crucial input for the high intensity, high luminosity Pb-Pb physics run scheduled for the end of 2023.

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